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RESOURCE LEVELING IN OPERATIONAL PLANNING

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RESOURCE LEVELING
IN OPERATIONAL PLANNING

by

RICHARD STEPHEN MOORE

B.S., U.S. NAVAL ACADEMY
(1961)

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Department of Civil Engineering
January 20, 1963

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ABSTRACT

RESOURCE LEVELING IN OPERATIONAL PLANNING

BY

RICHARD STEPHEN MOORE

Submitted to the Department of Civil Engineering on 20 January, 1964 in partial fulfillment of the requirements for the degree of Master of Science.

The Critical Path Method of planning and scheduling operations attempts to arrive at a schedule of project activities which results in the least cost. However, CPM does not consider manpower and machine requirements of the various activities. Therefore, great fluctuations in the daily requirements for these different trades or resources may invalidate the cost information associated with a CPM schedule. Several methods have been devised to adjust the CPM schedule so that resource fluctuations and maximum resource requirements are reduced. The ideal situation, however, is a constant level of resource usage which these methods do not obtain.

This thesis outlines the basic principles of the Critical Path Method and explains why resource considerations may be an overwhelming factor in arriving at an optimum project schedule. The various resource scheduling and schedule adjustment methods are described which attempt to solve the problem of resource fluctuations. The reasons for their lack of success are explained, the primary one being the assumption of constant activity crew size. A resource leveling technique is presented which should maintain a very nearly constant level of resource usage on most projects. And, finally, several suggestions are made for future work in the field of resource scheduling.

Thesis Supervisor: Mr. John A. Currie

Title: Lecturer in Civil Engineering

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I

INTRODUCTION

Following the worldwide industrial revolution in the 19th century, manufacturing and other industrial operations began to be increasingly complicated. Large mechanized industries developed and it became increasingly apparent that long range planning was necessary to insure successful operations. Thus the operational planner became an important figure in all industrial organizations. In the construction industry, the success of any operation is critically dependent on the judgement and accuracy of the planners and estimators. However, until recent years, these planners were forced to rely on their experience and professional judgement in planning and scheduling operations.

During World War II, the field of Operations Analysis developed using the basic principles of statistics and probability to plan more effective military operations. Out of this came the realization that industrial projects could also be planned with more quantitative methods. Thus more interest developed in operational planning and inevitably several techniques were developed.

In 1957, a technique of planning and scheduling projects was introduced at E.I. du Pont de Nemours Company which came to be known as the Critical Path Method. During the last

decade it has been developed by many others and several methods of solution have been derived. At the same time a very similar method called PERT was developed by the U.S. Navy and was partially responsible for the completion of the Polaris Missile far ahead of expectations. In the last few years a series of computer programs have been written which calculate results formerly derived by hand. Thus, large projects can now be planned quickly and with little effort the most profitable schedule is obtained. Today the Critical Path Method is widely used in manufacturing and construction projects and is, in fact, required on all construction contracts with the U.S. Government.

However, along with project planning and scheduling came the problems of scheduling resource requirements. In this context the word "resource" refers to the men and machines required by a project. For instance a construction project may require carpenters, steelworkers, painters, cranes, steam shovels, and bulldozers. Each one of these is a resource. "Resource requirements" or "resource usage" refers to the quantity of man-days or machine-days of a certain resource required by a project. The resource usage on one certain day refers to the number of men or machines required by the project on that day. This brings up the concept of resource leveling. While the overall resource requirements of a project cannot usually be changed, the

resource usage on any particular day is quite variable. The object of resource leveling is to balance the resource requirements of a project over the length of the project so that the resource usage on each day of the project is the same or very nearly so. In other words resource leveling tries to obtain a constant level of resource usage over the duration of a project. This must be done separately for each resource required by the project. It is realized that such an absolute level of resource usage is not possible or even desirable on most actual projects. However, it is the ideal and most economical situation and the goal for which any resource leveling technique should strive. It should be noted that resource leveling as described in this paper differs considerably from most resource allocation techniques which only seek to restrain daily resource usage below a certain maximum.

The object of this thesis is to develop a mathematical technique for resource leveling which can be easily computed by hand or programmed for a digital computer. In this way it can be economically used on both large and small projects. The usefullness of this technique will be greatly increased when it has been converted into an operating computer program. It is suggested that this be the subject of a future thesis in this department.

Those familiar with the Critical Path Method may prefer

to omit reading the following section, possibly referring only to the diagrams which form a basis for those in other sections. Throughout this thesis the construction industry will be used in the illustrative examples. However, it is certainly hoped and expected that with some small adaptive changes the technique presented could be used for the manufacturing and other industrial processes.

II

THE CRITICAL PATH METHOD

In this section the Critical Path Method itself will be discussed. It should be understood that CPM will not be explained fully. It will only be discussed to the extent necessary to give the reader a background and insight into the problems which make a resource leveling technique necessary. For a more complete understanding of CPM the reader should familiarize himself with Lecture Notes on Critical Path Scheduling by J. Lloyd Cutcliffe. (1)

CPM is divided into two phases - the planning phase and the scheduling phase. Basically the planning phase consists of breaking a project or operation down into activities. In a typical construction project an activity might be: "erect framework for second deck floor slab". The beginning and the end of an activity are known as events. Once the project is broken down as far as possible into separate activities, the activities and events are arranged in an arrow diagram. The arrow diagram illustrates which activities must be completed before others can begin. Activities are represented by arrows and events by circles. The length on any arrow has no meaning, but care must be taken to insure that an arrow preceeds or follows only those other arrows which it must. In other words, activities must proceed in

a logical sequence. Certain activities must be completed before others can begin and the arrow diagram must accurately reflect this. In many cases several activities may take place at the same time. In the diagram, events must be numbered so that every arrow ends at an event with a number greater than the number of the event at which it started. A typical arrow diagram for part of a project is shown in Figure II-1 on the following page.

For the scheduling phase it is necessary to determine cost information for each activity. For this purpose a time-cost curve is developed for each activity. In general, if an activity is completed in a normal amount of time with an efficiently sized crew, it will require a certain number of man-days to complete and will have a certain cost associated with this. Since material costs are constant regardless of activity duration (neglecting wastage) they are not considered in the CPM analysis. Therefore the activity cost is usually a direct multiple of the number of man-days required. This multiple, of course, varies with the wage rate of the men working but for rough purposes can be assumed to be an average value for all activities and trades. As an example, assume an activity normally requires 48 man-days to complete. An efficient-size crew may vary from 3 to 12 men. Therefore the activity may be completed efficiently in a period of from 4 to 16 days. If

SAMPLE ARROW DIAGRAM (1)

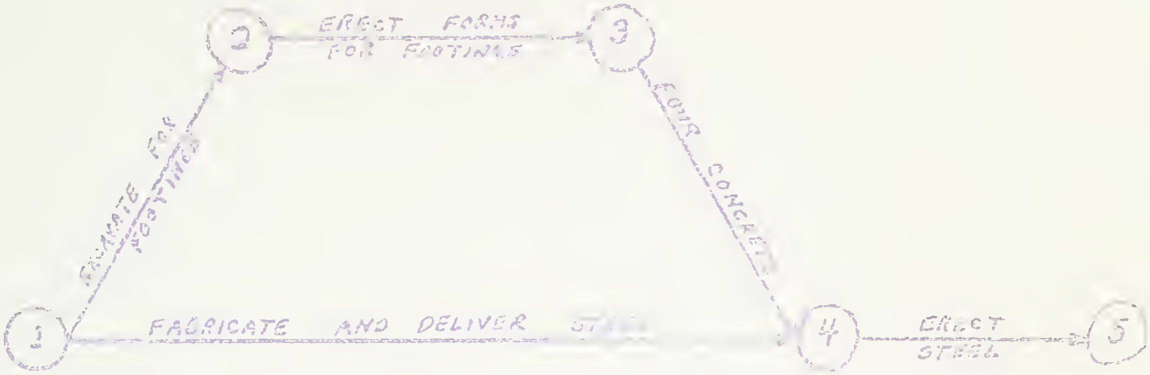

FIGURE II-1

ACTIVITY TIME-COST CURVE

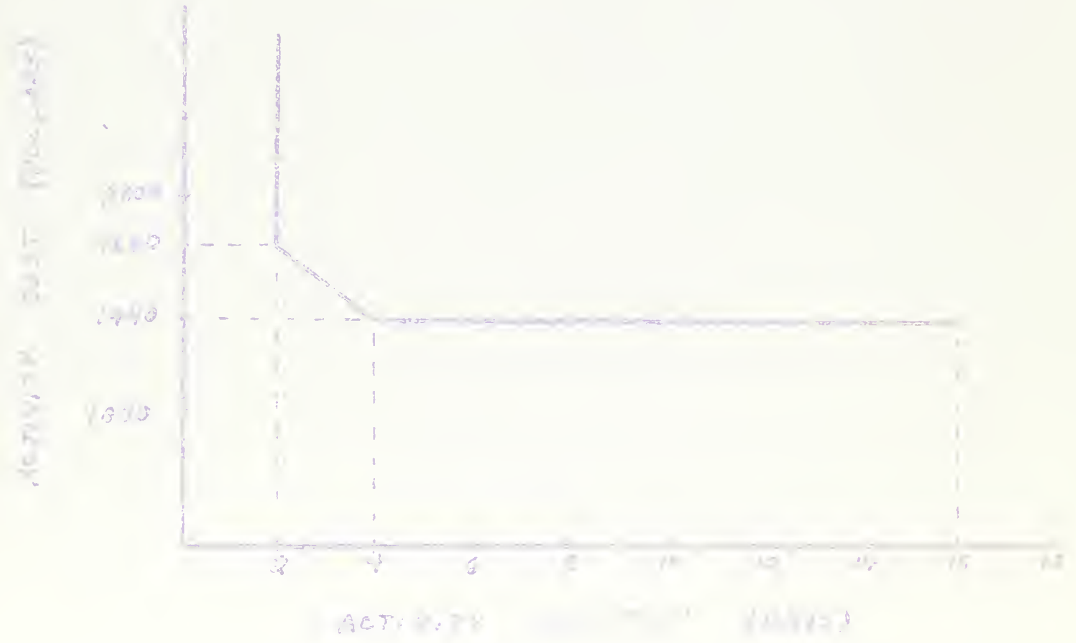

FIGURE II-2

it is necessary to complete the job in 2 days it may take 56 man-days and therefore a crew size of 28 men. The greater number of man-days are caused by the fact that 28 men cannot work efficiently on this activity, possibly because of limited space. Assuming an average wage rate of $30.00/day/man, this activity would cost $1440.00 to complete in 4 to 16 days and $1680 to complete in 2 days. It is assumed that the activity cannot be completed in less than 2 days. Assuming a linear relationship between 2 and 4 days the time-cost curve shown in Figure II-2 is derived. It can be assumed that a crew of fewer than 3 men would either be impossible or inefficient. Therefore the cost of completing the activity in a duration of greater than 16 days would be either infinite or some value greater than $1440.00. Long durations such as this can be ignored since they would never be included in any least-cost schedule anyway. Normally in a CPM analysis any duration longer than 4 days for this example activity would be neglected because the cost cannot be decreased by lengthening the activity beyond this point.

The scheduling phase uses the arrow diagram and the time-cost curve for each activity to produces a marginal time-cost curve for the entire project which may look like the diagram in Figure II-3. Again, straight line segments are drawn between calculated points. To the values of direct cost obtained for each duration from this curve are added the indirect or overhead costs associated with this parti-

DIRECT COST CURVE

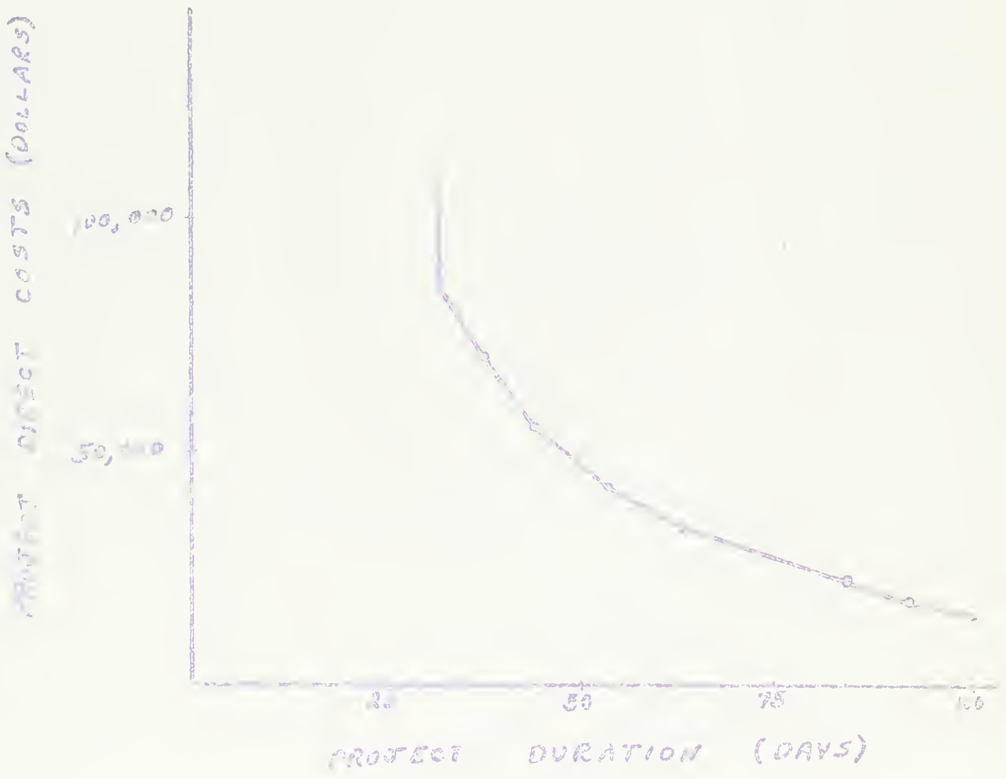

FIGURE II-3

cular duration. The indirect costs can normally be considered a constant cost per day and therefore increase linearly with duration.

Figure II-4 shows a typical indirect cost curve and a curve which represents the sum of direct and indirect costs is shown in Figure II-5. The point on Figure II-5 at which total cost is a minimum is usually chosen as the optimum duration. The Critical Path Method, therefore, indicates that duration at which a project can be accomplished at least cost. However, if there is a previously specified completion time shorter than the optimum, this duration must be chosen instead, even though the total project cost will be greater.

For each calculated completion time a schedule is also produced which gives the time of each event necessary in order to complete the project in this duration. The information produced for each schedule is the scheduled duration of each activity, the earliest possible time of each event, the latest possible time of each event, and several other quantities known as floats. The arrow diagram in Figure II-6 illustrates some of these quantities. The number over each arrow is the scheduled duration of that activity. The number circled near each event is the earliest possible time of that event and the number inclosed in a square is the latest

INDIRECT COST CURVE

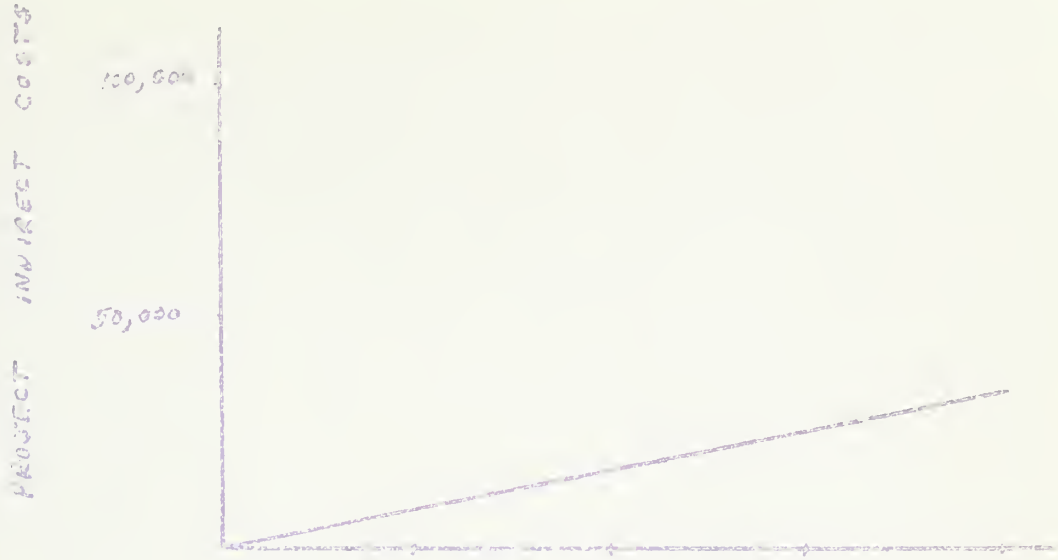

FIGURE II-4

TOTAL COST CURVE

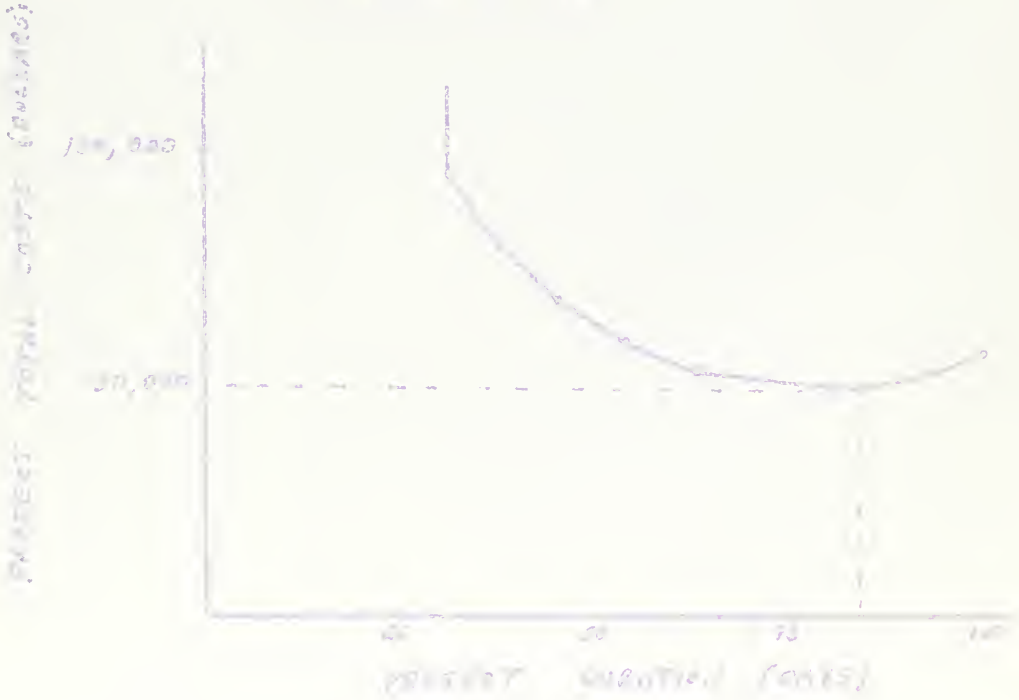

FIGURE II-5

CRITICAL PATH DIAGRAM

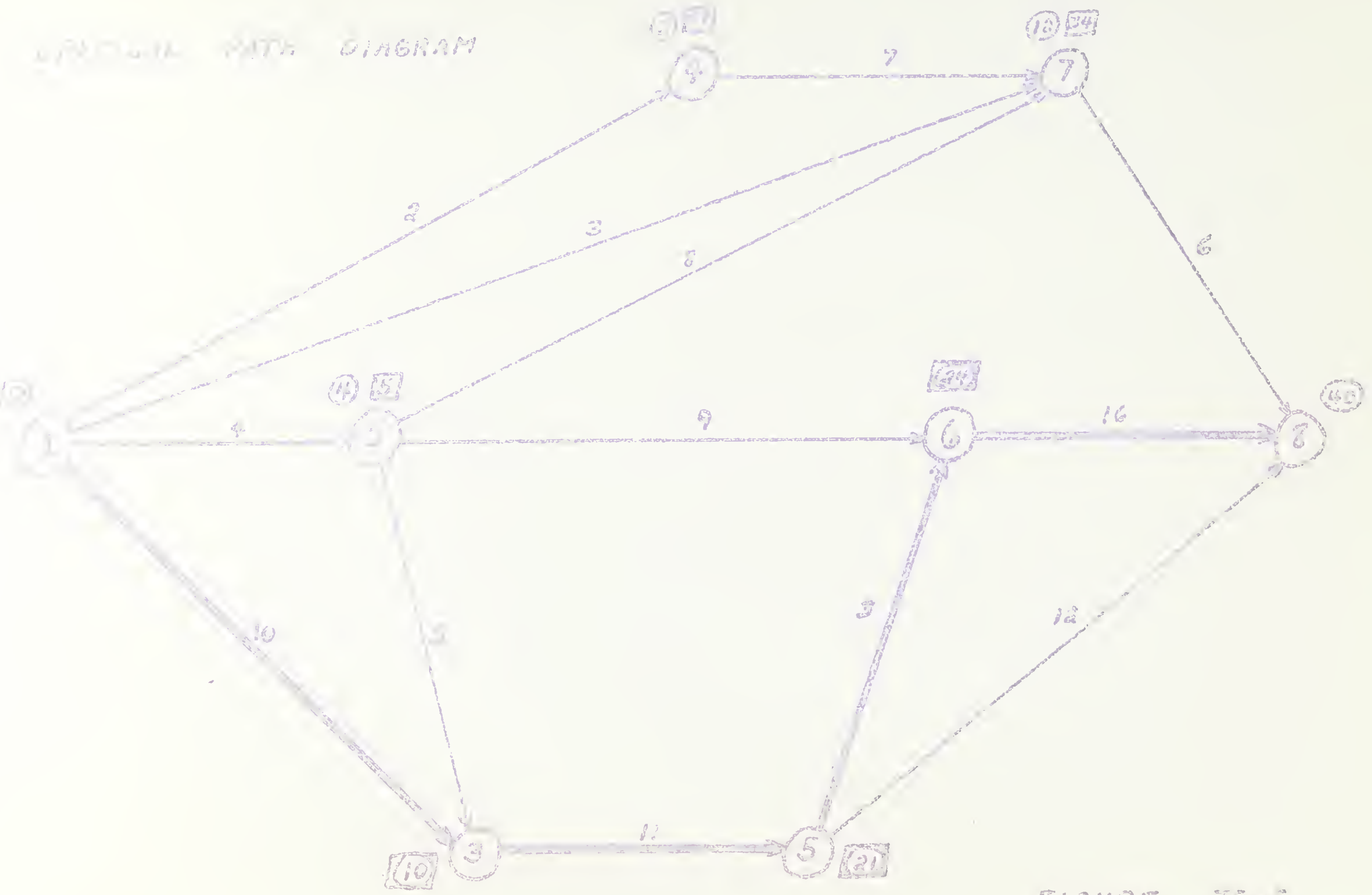

FIGURE II-6

possible time of that event. Examination of these quantities should indicate how they are derived. This is how the arrow diagram might appear with the final schedule information indicated on it. The project is assumed to start at time zero and the completion time is the time of the final event.

The float of an activity can be defined roughly as the leeway allowable in the scheduling of that activity. More specifically, consider the activity which is preceded by event i and followed by event j. If:

t^{E}_{i} = the earliest possible time of event i
t^{L}_{i} = the latest possible time of event i
t^{E}_{j} = the earliest possible time of event j
t^{L}_{j} = the latest possible time of event j, and
t = the scheduled duration of this activity i-j;

then the floats for this activity can be defined as follows:

$$\text{TOTAL FLOAT} = t^{L}_{j} - t^{E}_{i} - t$$

This is the amount of time that the activity can be lengthened without changing the completion time of the project. Part of this float may be shared with the preceding and the following activities. For example, the total float of activity 4-7 in Figure II-6 is 25 days.

$$\text{FREE FLOAT} = t^{E}_{j} - t^{E}_{i} - t$$

This is the amount of time that the activity can be length-

ened without changing the earliest possible starting times of the activities immediately following it. Part of this float may be shared by preceding activities. The free float of activity 4-7 of the example project is 3 days.

$$\text{INDEPENDENT FLOAT} = t_j^E - t_i^L - t$$

This is the amount of time that the activity can be lengthened without changing the earliest possible times of following activities or the latest possible times of the preceding activities. This float is not shared with any other activities. Activity 4-7 has no independent float. The independent float of activity 5-8 is 7 days.

Those activities which possess no float are called critical. They must be performed at the scheduled time in order that the project completion not be delayed. No leeway is available for these activities. These activities form a continuous path from the start to the end of a project. Hence the term "critical path". In the arrow diagram of Figure II-6, the critical path consists of the activities 1 - 3, 3 - 5, 5 - 6, and 6 - 8.

III

THE RESOURCE PROBLEM

To this point there has been no mention of resource usage except in the development of the activity time-cost curves. In scheduling activities no consideration has been made of the possibility of excessive resource requirements due to simultaneous requirements by several activities. Herein lies the major drawback of the Critical Path Method as it presently exists. Requirements for a particular resource may fluctuate radically from day to day. A bar chart representation of the project diagrammed in Figure II-6 may illustrate this point. Such a chart is shown in Figure III-1. The bar chart shows each activity represented by a bar beginning at its earliest possible starting time and continuing for the scheduled duration. Consider one specific resource for the moment, for example carpenters. The figures above each bar indicate possible requirements for carpenters by that activity during each day of its duration. In this example it can be seen that 10 carpenters are needed during the first 2 days, 13 the next day, 7 the next, 15 on the fifth day and so on. It is quite possible that on a larger project with more simultaneous activities, these fluctuations could be much greater. When

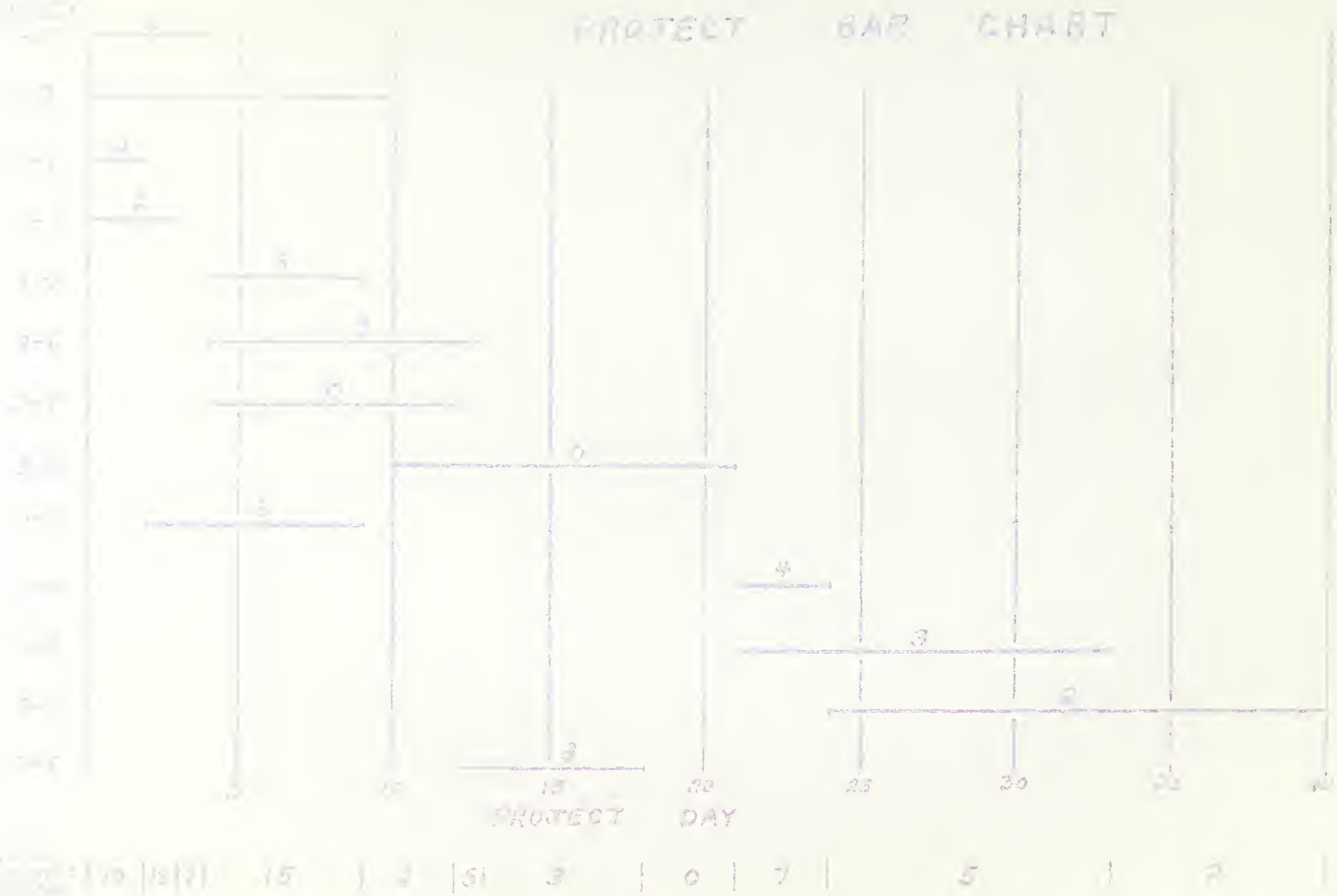
PROJECT BAR CHART
5
10
15
20
25
30
35
40
PROJECT DAY
4
3
2
3
15
3
5
3
0
7
5
1
2

FIGURE III-1

other resources are brought into consideration it is obvious that quite a serious situation can develop. Because of the nature of the Critical Path Method, it is normal for several resources to have peak requirements at the same time. Any businessman can see that a situation like this is to be avoided at almost any cost. But as CPM exists now, there is very little that can be done. Certain attempts have been made to keep resource requirements below a certain maximum limit and they will be explained in detail in the next section.

There are several reasons for wanting to level resource usage. The first one usually considered is the limit of availability. Certainly, if one can only hire 10 carpenters, then something must be done to alter the schedule diagrammed in Figure III-1. This is the factor most often considered in resource allocation methods but there are others which may be far more important in the long run. Suppose it is possible to hire a sufficient number of carpenters for any requirements you might have. For the example problem you would hire 10 carpenters on the first day. On the third day you must hire 3 more. On the forth day you need only 7 of these. Here is the problem. Do you fire the other 6 and hire them back plus 2 others on the fifth day? Or do you retain the extra 6 carpenters on

the payroll even though there may be no work for them on the fourth day? There is a certain processing cost associated with each time you hire or fire a man, not to mention the payroll and accounting problems which would be encountered with frequent change in personnel. Ideally you would like to hire a certain number of men on the first day and retain them until the project is completed. In addition to the extra costs associated with frequent hiring and firing is the loss of confidence and good will. There are without doubt a great many benefits to be derived from being a "project-life employer". However, you do not want to retain idle personnel on the payroll. Certainly you would not hire 15 carpenters for the entire 40 days of the example project.

The most common method of reducing maximum resource requirement levels is through use of the floats. A great deal of research has been conducted in recent years on different methods of using floats to adjust activity starting times and thereby lower maximum resource levels. Several computer programs have been developed to accomplish this most effectively. Some of them will be discussed in the next section. There is no evidence, however, that any techniques are available which maintain a constant level of resource usage. Smaller fluctuations are

possible through the use of float adjustment methods, but not usually a constant level. Again, the bar chart can be used to illustrate this technique. In the example a great deal of float was available for activities connecting events 1, 4, 7 and 8. If activity 4-7 requiring 5 carpenters is delayed until after the completion of activity 2-3 which requires 8, then the maximum requirement for carpenters is reduced from 15 to 10. See Figure III-2 for an illustration of this change. This delay affects only one other activity. The earliest possible time of event 7 is now changed from day 12 to day 16 and activity 7-8 must be delayed until this time. However it is evident that the project completion is not delayed and direct costs for the project are in no way altered.

Further use of float to alter activity starting times could bring maximum requirements even lower and possibly even bring the maximum fluctuation within one or two men. However it should be remembered that this is an extremely simple example and it is on larger projects with many more simultaneous activities that this method has been observed to be ineffective in reducing fluctuations. The work of John R. Brach which demonstrates this fact will be discussed in the following section. Also, only one resource has been considered. When several other resources are added to the

ADJUSTED BAR CHART

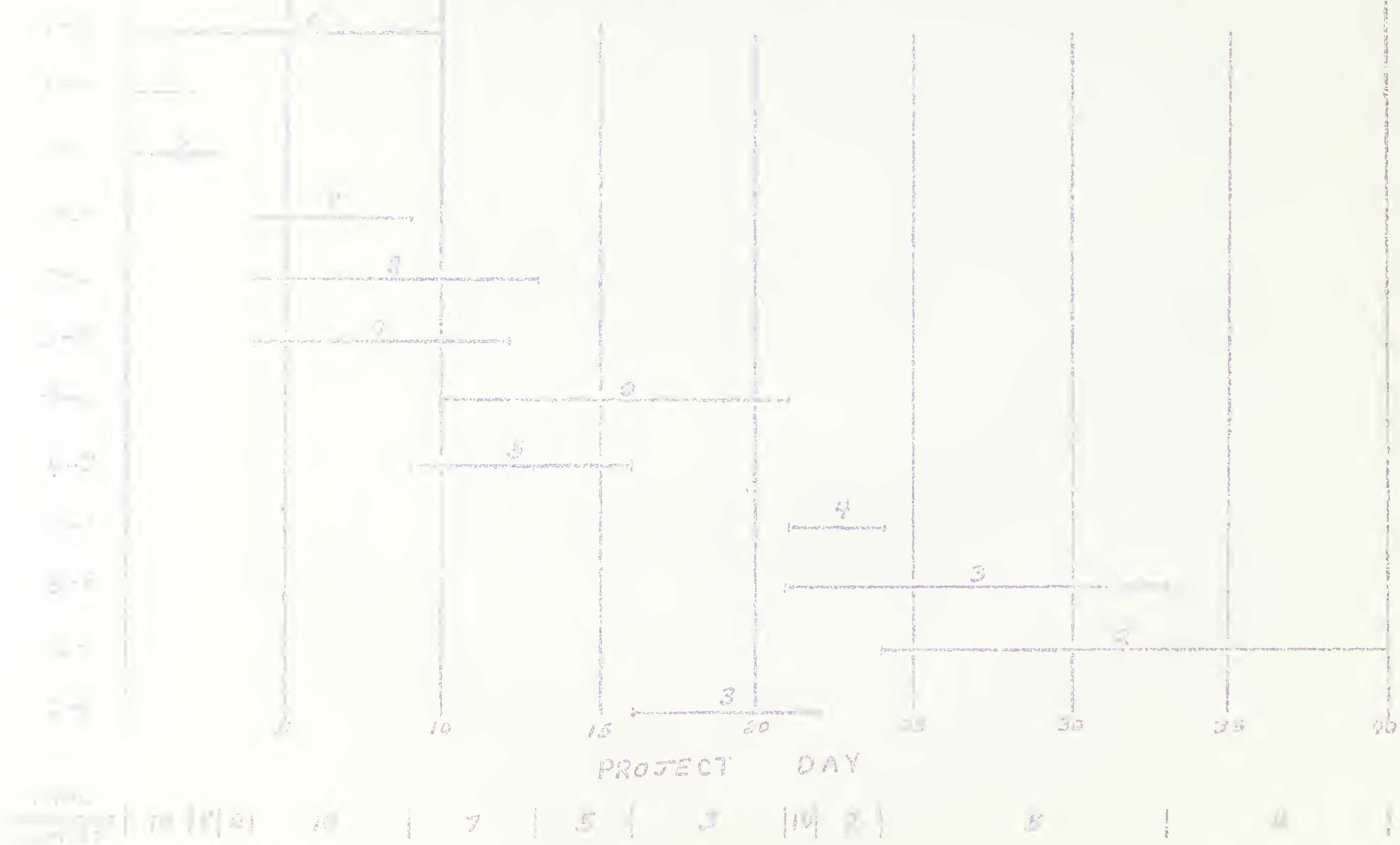

FIGURE III-2

problem and when it is considered that in many projects, the amount of float available will be very limited, it is readily seen that the possibility of resource leveling by this method is, at best, very tenuous.

Graphs of resource usage versus time on the project might illustrate better what is desired in the way of resource leveling. For the original schedule of the example problem the requirement curve for carpenters would look like that in Figure III-3. The area under this curve, of course, represents total carpenter man-days required for the project. After adjustment of float on activities 4-7 and 7-8, the curve would appear as in Figure III-4. For ideal resource leveling one would desire a curve for this project such as the one shown in Figure III-5. However, it is doubtful if this is possible on most projects and certainly a fluctuation of one or two men is not infeasible in a technique where input information is only an educated estimate. Variations in worker productivity can cause changes on the job which completely obscure small fluctuations in resource scheduling. Also since fewer activities are normally in progress during the several days at the beginning and end of a project, resource requirements will usually be lower at these times. The resource requirements of a large project would probably reach a peak sometime

PROJECT RESOURCE USAGE

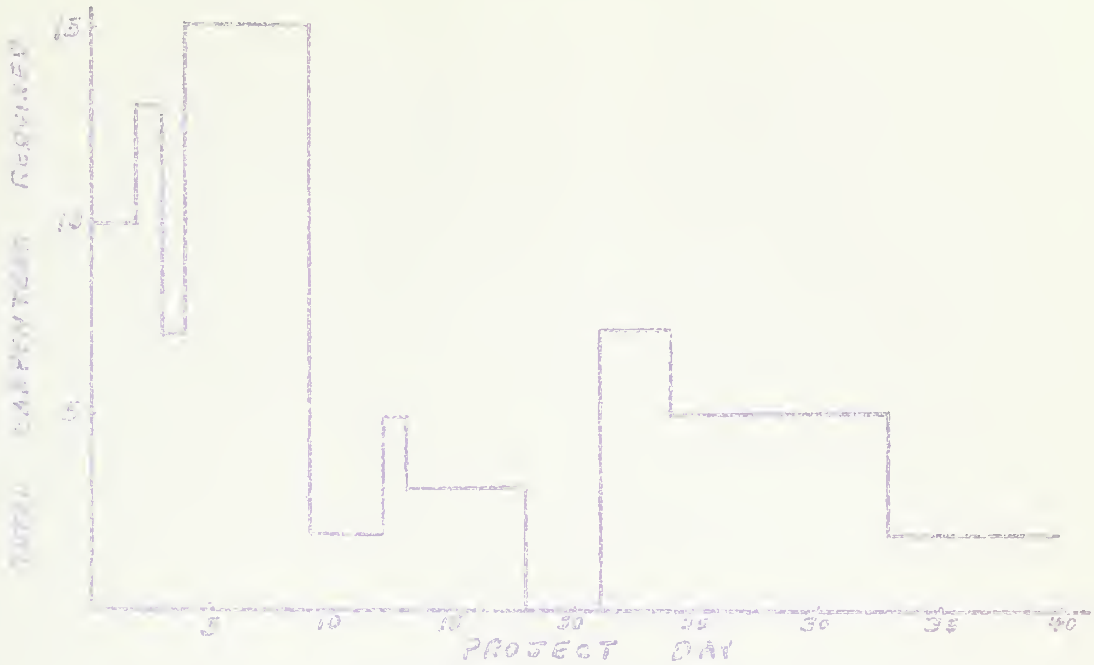

FIGURE III-3

ADJUSTED RESOURCE USAGE

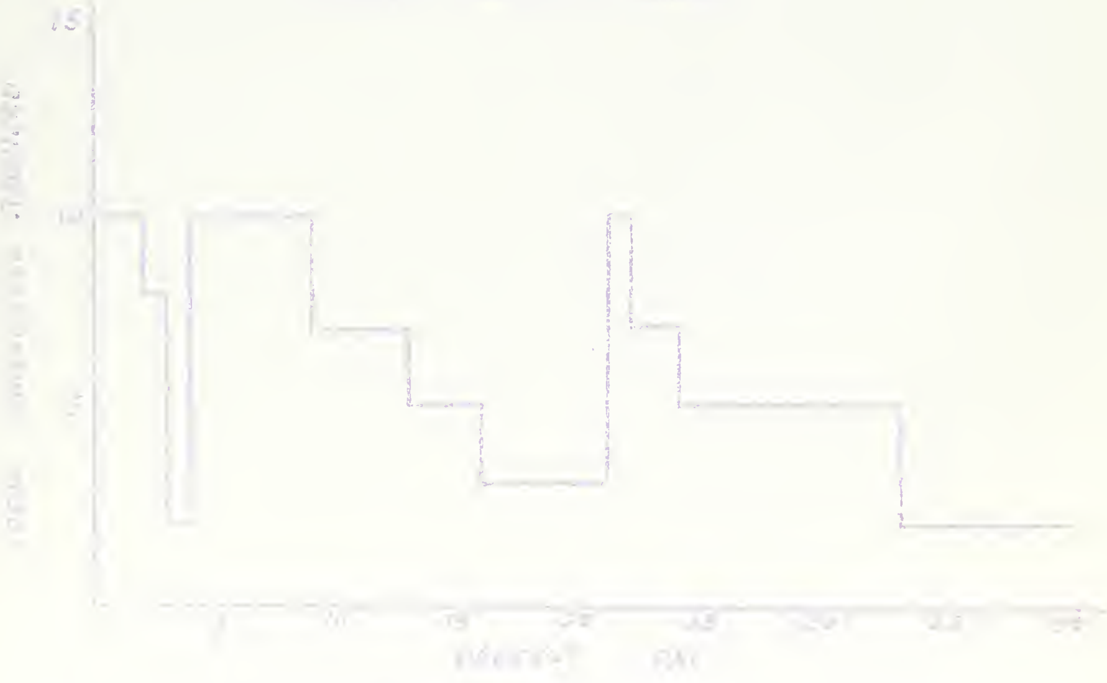

FIGURE III-4

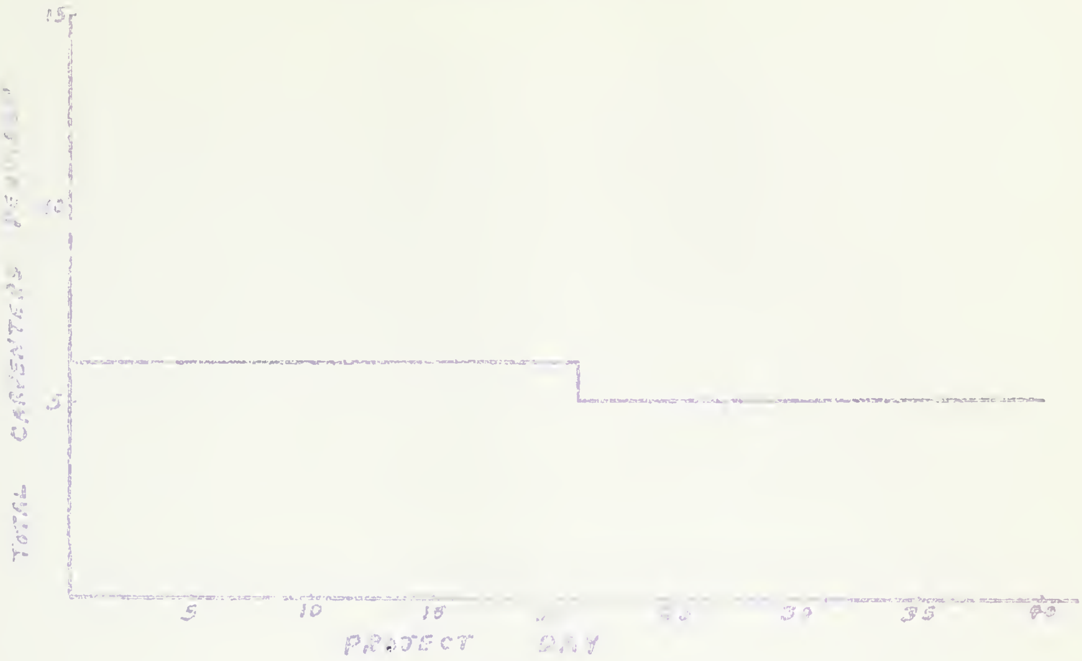
IDEAL RESOURCE USAGE

FIGURE III-5

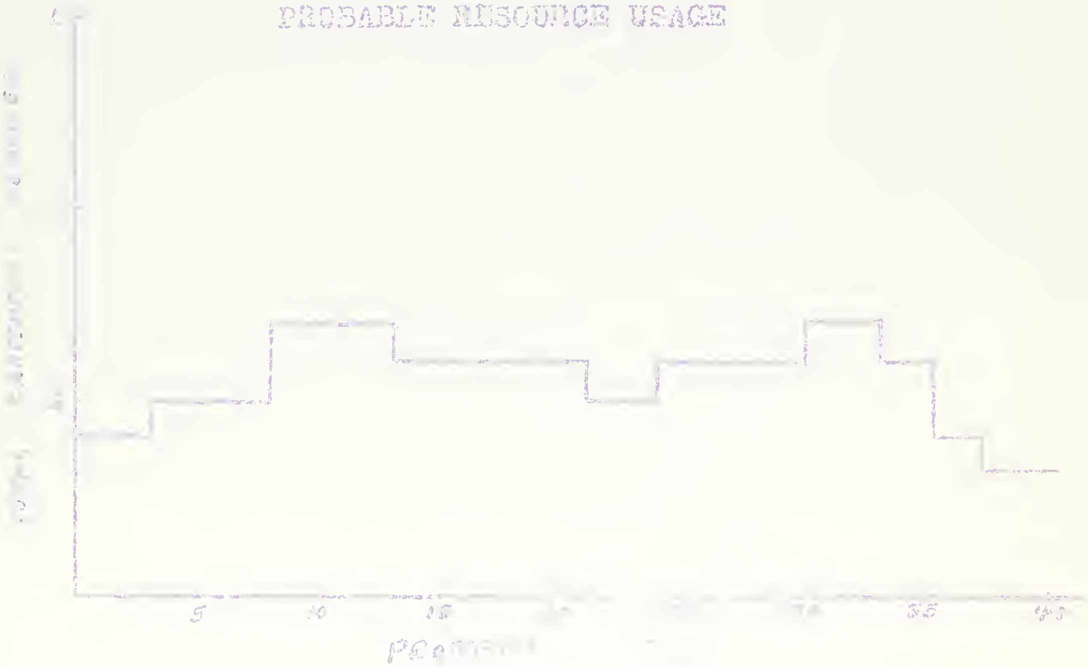
PROBABLE RESOURCE USAGE

FIGURE III-6

near the half-way point in the completion of the project. Therefore, a resource usage curve such as the one shown in Figure III-6 might be perfectly acceptable. However, a constant level is still the ideal situation, even though it may not be achieved on many actual projects. The factors mentioned above are merely restrictions imposed on any resource leveling technique by the project itself.

It should be remembered that the total carpenter man-days required for the project completion is a constant. Therefore, the areas under all four resource curves must be equal. This, of course, assumes that efficient conditions and constant productivity are maintained. The only situation to be strictly avoided is that in which large dips occur in the middle of the curve. This is the situation in which high cost of retaining idle personnel can negate any value which a critical path schedule might otherwise have.

IV

RESOURCE SCHEDULING METHODS

Due to the spread of the Critical Path Method there has been a great deal of interest in recent years in the resource scheduling problem. Many of the same private concerns which originally developed the Critical Path Method have attempted to find solutions to this problem also. There is only limited information available concerning the majority of these solutions. Several will be explained briefly in this section.

Resource Planning and Scheduling Methods (RPSM) developed by Mauchly Associates (3) is what is generally referred to as a "serial" method. Activities are ranked according to ascending terminal event numbers and then scheduled one at a time. An activity is scheduled at its earliest possible time unless a predetermined resource availability limit is exceeded in doing so. In this case the activity is delayed until such time as it can be scheduled without exceeding the set limit. The method allows an activity to be split into sections if the resource limit permits its start but makes it necessary to delay part of the activity before its finish. A limit is imposed on the extent to which an activity can be delayed. If an activity

is delayed to this limit, it is scheduled at this regardless of excess resource usage. It appears that all resources are considered simultaneously in this method and that usage of all resources must be below their respective limit in order to schedule an activity. A basic CPM analysis is used initially to determine the scheduled duration of each activity and therefore its daily resource usage. The reason for this is not clear. It would seem that since the schedule derived by the Critical Path Method is made obsolete by the resource scheduling considerations; that the activity durations given by the Critical Path Method might not be optimum for the final schedule derived by RPSM. In other words, it would seem logical that the activity duration would be optimum only in the particular schedule for which they are derived and not in another schedule obtained by delaying a number of activities.

Resource Allocation and Multi-Project Scheduling (RAMPS) developed by E.I. du Pont de Nemours and Co. (4) and Job Leveling developed by W.C. Hillemeyer of the Cities Service Petroleum Company (5) are referred to as "parallel" methods. These methods, instead of scheduling one activity at a time, choose out of all those activities which can proceed at a certain time, a group of activities which do not exceed resource limits. This group is usually chosen so that the

activities with the least total float are chosen first. The major drawback to this method is that there is no simple way to determine if this group so chosen leads to the optimum solution. RAMPS attempts to solve this problem by testing many different combinations of activities for the chosen group. However, it would be very impractical to try to test all possible combinations in a large project to determine which is optimum. RAMPS also allows splitting of activities as in RPSM and further considers the lengthening of activities when possible in order to obtain a lower daily resource usage. Job Leveling contains another refinement in that it computes a revised total float for activities which may be delayed. This revised total float is used instead of the original float to choose that group of activities which should proceed at a certain time. This refinement aids in obtaining a nearer-optimum solution but there is still no assurance that the optimum is accomplished.

Another and generally less effective method of reducing maximum resource usage was used by J.R. Farmer in his CPS 200 (6). This is what was described in the previous section as adjustment of float. The average usage level for each resource is computed and floats are allocated among non-critical activities in an attempt to maintain resource usages as close to these averages as possible. Event times

and floats are recalculated each time an activity is adjusted and several complete runs through the entire project are usually required.

J.D. Kidd in his CRS 333 (7) attempted to improve on the method used by Farmer. CRS 333 first attempts to reduce the maximum resource usage to as low a level as possible by the adjustment of floats. There are two limits which the method tries to meet - a critical limit, above which resources are assumed to be unavailable, and a desired limit. If the critical limit is exceeded at any time after floats have been adjusted, an indication of this is given. The arrow diagram can then be altered, possibly lengthening the project or using another schedule given by the original CPM analysis. The allocation of floats proceeds again as before and it may be necessary to repeat this process several times. In the end it may be necessary to adjust the time-cost curve for the project to reflect the remaining resource fluctuations or excess usage above the desired limit.

In "An Application of Resource Allocation Techniques", (8) John R. Brach describes certain tests that he made on Kidd's CRS 333. On the test project used, CRS 333 accomplished a negligible amount of resource leveling which would indicate that a great deal of diagram revision would

be necessary on most projects before a satisfactory amount of resource leveling is accomplished. This revision would in most cases lengthen the project to an unacceptable extent, thereby invalidating the whole technique. Brach, however, suggests that CRS 333 might be applicable where resource limits are not very stringent. It would appear that a great deal of available float is necessary to arrive at desirable results with this method.

King Royer in "CPM vs. Cost Control" (9) makes several good suggestions. This article gives an excellent brief explanation of the resource problem and how it affects the supervision on the job. It suggests that in order to reduce maximum resource usage, all events be scheduled at their earliest possible time and all activities lengthened to make use of the then available float. This makes all activities effectively critical on a time basis but usually reduces resource usage below the critical level of availability. However, Royer goes further to suggest that the resource requirement of an activity can be considered a constant regardless of the duration assigned to the activity. In other words, he assumes that an activity will require, for example, 18 man-days whether it is done in 2 days with 9 men or 9 days with 2 men. This assumption is not considered valid in most cases. In this example 9 men may inter-

fere with each other to such an extent that 3 days are required for them to complete the activity. It can be seen that Royer's assumption is contrary to the basic principles of the Critical Path Method and though CPM is certainly not the last word, it can be assumed that it is reasonable in this matter.

As previously mentioned, the major objection to all the methods discussed is that they do not necessarily level resource usage. All these techniques attempt to adjust the times at which certain activities are in progress so as to reduce the maximum resource usage below a certain level and maintain it as close as possible to an average. The first of these goals is accomplished very easily by most of these methods but results toward the second goal must be considered unsatisfactary. At present, there does not seem to be an available technique which allocates resources to activities in such a manner as to maintain even a near-constant level of usage.

V

A RESOURCE LEVELING TECHNIQUE

To this point, it has been assumed, apparently by everyone concerned with the resource allocation problem, that the number of men employed on a certain activity must remain a constant throughout the duration of the activity. That is, the amount of each resource required by an activity must be the same for each day of the duration. If an activity requires 24 carpenter man-days for its completion and its scheduled duration is 4 days, then the assumption has been that 6 carpenters must be assigned to this activity during each of these 4 days. While this constant crew size is a desirable goal, it is usually not a very good representation of what actually takes place on a job. There are a great many factors which may make it necessary to assign 7 carpenters one day and 5 the next to the activity mentioned above.

Consider how the man-day requirements for a particular activity are derived. The basic knowledge from which to proceed is the amount of material to be placed. That is, it is known beforehand how much framework is required for a certain floor slab and how much lumber is required to erect this framework. Next, an estimate is made of

productivity per man, that is, how much framework can be erected (lumber placed) by one man in one day. This figure must necessarily be an average derived from experience and observation. When this second figure is divided into the first, the number of carpenter man-days required by the activity is obtained. To obtain cost, this figure is multiplied by the wage rate for carpenters. To obtain average crew size, the number of man-days is divided by the scheduled duration. However, this average crew size cannot often be maintained. Suppose the productivity of several of the carpenters is below the estimate. After the activity has progressed for a few days and it is found that it is lagging behind schedule, it may be necessary to increase the crew size by one or two men for the last part of the activity. The same situation may exist if a man is taken off the job by illness or accident. An accident could also destroy part of the completed work. In cases like these it would be desirable to take men off of activities that are progressing well or ahead of schedule, and put them on the delayed activity so that it can be completed on time. This has the effect of decreasing the crew size of one activity and increasing that of another.

For this reason it is felt that constant crew size does not need to be a strict assumption but should merely

be a desirable aim of any resource allocation technique. This does not change the fact that man-days required is still the basic quantity associated with any activity. Nor does it change the cost information which is input information to the scheduling phase of the Critical Path Method. It must be assumed, of course, that the crew size always remains within the limits of an efficient-size crew for each activity. If the crew size is allowed to fluctuate outside these limits, the cost of the activity will be increased accordingly. For this reason, activities which are critical must be considered separately. Critical activities usually have a scheduled duration which requires a crew size that is either equal to or greater than the maximum efficient crew size for the activity. Therefore, the crew size of all critical activities must be constant in order not to increase the inefficiency of the crews and thereby increase costs. This usually presents no problem since in most projects only a relatively small percentage of the activities will be critical in the optimum CPM schedule.

With the assumption of variable crew size, the problem of resource leveling is greatly reduced. The basic critical path analysis can be used as a starting point for resource leveling as in some of the resource scheduling methods described in the preceding section, but with much more success.

Now, instead of merely shifting activity times within small limits in order to reduce resource conflicts, resources can be truly allocated to activities day by day in such a way as to maintain a constant level of usage. In this section a technique will be described which attempts to accomplish this.

As previously mentioned, the primary purpose of this technique is to maintain a constant level of requirement for each resource throughout the entire duration of the project. Secondarily, it is desirable to maintain a fairly constant level of resource usage for each activity throughout its duration. Basically, the method starts with the results of the Critical Path Method. A particular duration is selected (usually the one leading to the least total project cost) and the schedule associated with this duration is analyzed. All critical activities have only one possible duration because they cannot be lengthened without delaying the project completion. The non-critical activities all have varying amounts of float. In this method, all events are scheduled at their earliest possible time and each activity is lengthened to last the entire time between its terminating events. That is, all critical or "crashed" activities are left at their scheduled duration and all non-critical activities are extended by the amount of their free float. This has the

effect of filling in time gaps in the project and making all activities effectively critical. Now a separate bar chart of the project is constructed for each resource to be leveled which includes all those activities in the project which require this resource. Under the bar representing an activity is written the total number of man-days or machine-days of this resource required to complete this activity. The bar chart of carpenter requirements for the example project discussed in section III is shown on the next page. This is of course for the original schedule without any adjustments of the earliest possible event times. It can be seen that those activities requiring no carpenters are not included.

The total number of man-days or machine-days of the particular resource required for completion of the project is now divided by the total length of the project. The result, rounded to the next higher integer is the desired level of usage for this resource to be maintained throughout the project. In the example, a total of 221 carpenter man-days are required for the 40 day project. This indicates that a daily requirement of 6 carpenters is to be desired. Therefore, the problem is still one of converting a usage plot such as Figure III-3 into one similar to Figure III-5. The outlook is now fairly optimistic, however.

ALTERED BAR CHART

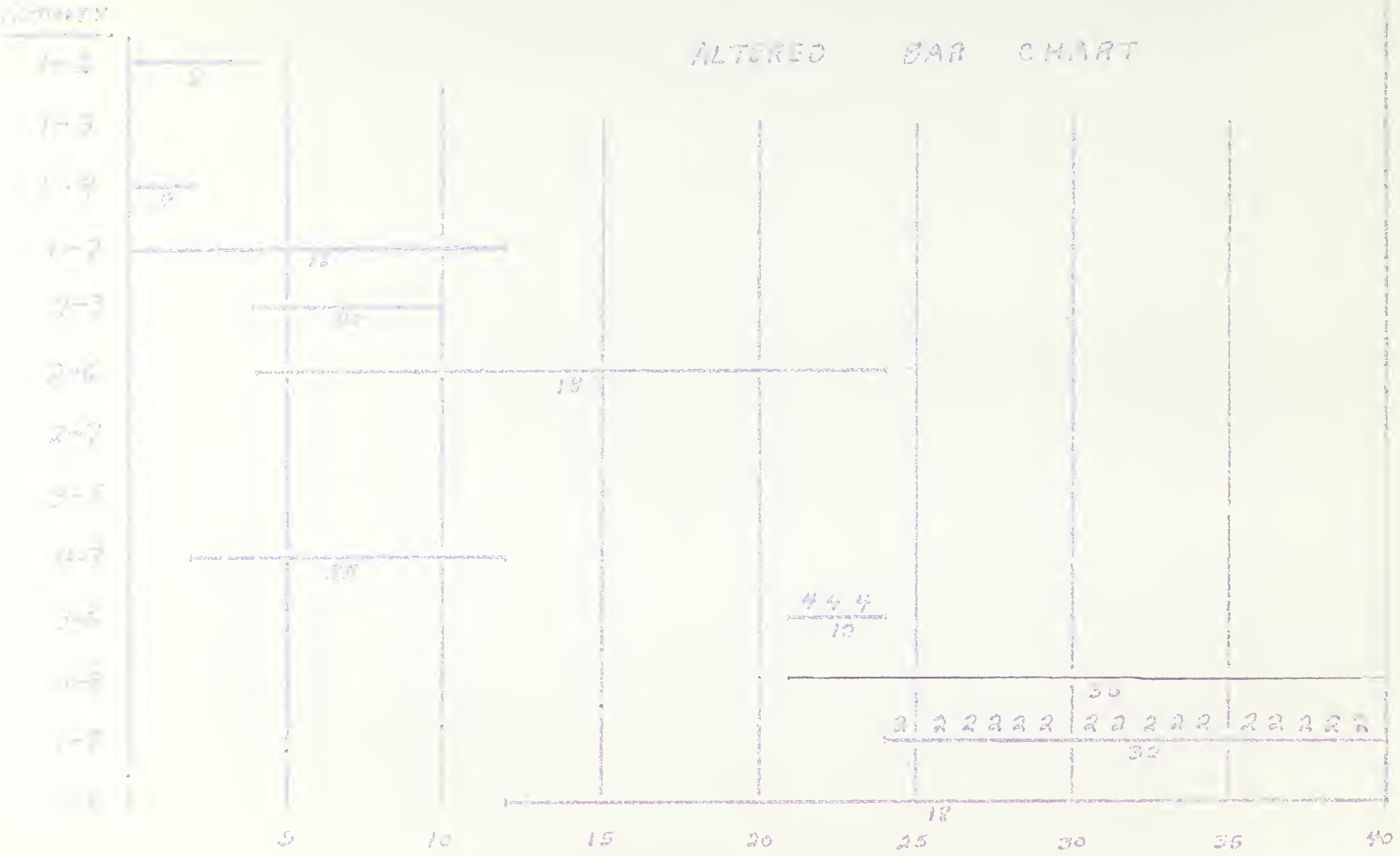

FIGURE V-1

The object is now to assign man-day (or machine day) units of the particular resource under consideration to all activities in progress on a certain day. Assignment begins with the first day and continues day by day to the end of the project. The basic restraint is that the total number of units assigned for a particular day should not exceed the desired resource level. As mentioned earlier, it should also be kept in mind that the number of units of a resource assigned to a particular activity should always be within the limits of an efficiently sized crew for that activity. Otherwise the cost of this activity will be increased and the total man-days figure associated with this activity will be incorrect. For this reason the units of resource usage should be assigned to critical activities first. Since these activities cannot be lengthened and since any increase in crew size will increase their cost, critical activities have only one possible crew size and therefore only one possibility for resource unit assignment. In the example, activities 5-6 and 6-8 are the only critical activities which require carpenters. Activity 5-6 requires 12 carpenter man-days and lasts 3 days. Therefore, 4 carpenters must be assigned to this activity for each day of its duration. Similarly 2 carpenters must be assigned to activity 6-8 for each day of its duration. These assignments can be seen in Figure V-1

written above the bars representing those activities. Once all critical activities have been assigned resource units, assignment then starts at the first day of the project and proceeds day-by-day as follows: For each day a quota is computed for each activity in progress on that day. The quota is derived by dividing the required man-days remaining to be assigned to the activity be the remaining length of the activity in days. Beginning with the activity which terminates earliest and proceeding in order of increasing terminating event time, each activity in progress is assigned a number of resource units equal to its quota rounded to the next higher integer. This assignment proceeds for each day until the desired resource level for the project is obtained. The final activity for a particular day to be assigned resource units may have to be assigned less that its quota in order for the total assigned units to be exactly equal to the desired level. However, it should be kept in mind that an activity is never assigned less than its minimum efficient crew. Of course, many activities may have no strict minimum for an efficient crew. When the desired resource level is reached by assigning less than an efficiently sized crew to an activity, the activity is assigned either no units or the minimum efficient crew, whichever brings the total units for that day closest to the desired level. If both quantities are

equally distant from the desired level the greater is chosen. That is, the minimum efficient crew is assigned to the activity, even though it may cause the total units for that day to be greater than the desired level. Table V-1 shows the limits of efficient carpenter crew sizes for activities in the example project.

If the desired resource level is not reached by assigning its quota to each activity in progress, then the remaining units needed to obtain the desired level are divided equally between all activities in progress, any remainder being assigned to the activity with the largest quota. If the quotas of several activities are equal, the units are assigned to the one with the greatest total resource requirements. Again, care should be taken not to exceed the maximum efficient crew size on any activity. If the quota for an activity on a certain day is greater than the desired resource level, a check is made to see if the terminating event of the activity can be delayed. If so, the total required man-days remaining to be assigned to all activities ending at this event is divided by the desired resource level. The event is delayed to the point where the number of days remaining in these activities is equal to the quotient obtained by this division, thereby using more of the total float of the activities concerned. If the terminating event cannot be delayed, the quota is

EXAMPLE PROJECT DATA

ACTIVITY	CARPENTER REQUIREMENT (MAN-DAYS)	MINIMUM EFFICIENT CREW	MAXIMUM EFFICIENT CREW
1-2	8	2	2
1-3	0	-	-
1-4	4	1	2
1-7	18	2	6
2-3	40	2	8
2-6	18	2	2
2-7	0	-	-
3-5	0	-	-
4-7	35	2	5
5-6	12	4	4
5-8	36	2	3
6-8	32	2	2
7-8	18	2	3
Total Carpenter Requirement (man-days)	221		

TABLE V-1

assigned to the activity at its present length and certain changes made later which will be explained. If at any time the quota of an activity becomes exactly equal to or greater than the maximum efficiently-sized crew, this activity is considered critical and must be assigned its quota for the rest of its duration. In the daily assigning of units it may be found that several activities have the same termination day. In this case the activity with the smallest quota takes precedence and assignment proceeds in order of ascending quota. Figure V-2 shows the example project after it has been completely assigned. Activity 7-8 of this diagram illustrates a frequent occurance of this method. This activity requires 18 carpenter man-days. However, when one arrives at day 28 an assignment of the remaining one man would be below the efficient crew size. Therefore, the minimum efficient crew must be assigned even though it increases the total man-days for this activity and for the entire project.

After the entire project has been assigned, it may be desirable to change certain factors and run through the procedure a second time. For instance if an activity had to be assigned a low number of units over a great deal of its length because of simultaneous early-terminating activities, it might be left at the end of its duration with an extremely

INITIAL RESOURCE ASSIGNMENTS

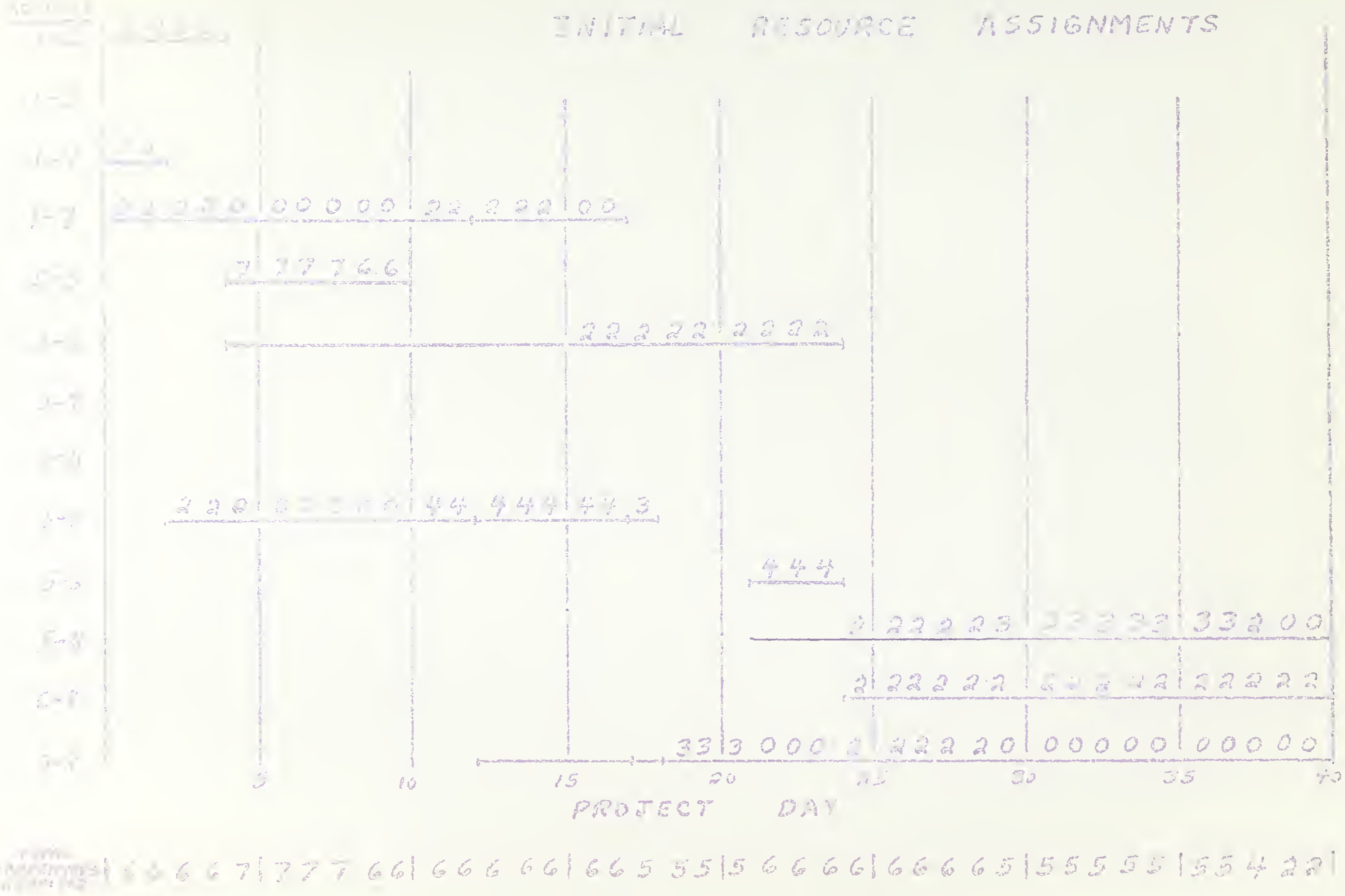

FIGURE V-2

high quota and no possibility of lengthening. In this case it would be well to raise the desirable resource level over a certain range in order to spread out the required man-days over the length of the activity. This could be done by considering all activities which terminate with or before the troublesome activity to be a separate project from those following and compute two separate desired resource levels. In that case the range of the desired resource levels would be from the beginning of the project to the event which terminates the troublesome activity and from this event to the project end. All critical activities which span over this division of ranges would have to be split for this purpose. The part which lies in each range would have to be considered with its respective range.

Another change which might be desirable in a second run is different event times. In the example it is seen that several activities are effectively split into two activities. There is a period of days during the activity in which no units of resource could be assigned to the activity. A splitting like this which leaves an activity dormant for several days may be undesirable. For this reason it may be wise to delay the starting time of an activity until it can be completed in one continuous series of days. This is not always true since many activities are often left dormant

over week-ends as a normal practice and a few days longer would make little difference. In other cases it might be desirable to change the limits of the efficient-size crew on certain activities in order to get a more constant crew size. The upper limit of an efficient-size crew is, in general, a fairly flexible value and may often be increased as well as decreased. In Figure V-3 is shown the assignment for the example project after the following changes are made: Activity 1-4 is delayed until day 2 thus delaying event 4 until day 4. Activity 1-7 is delayed until day 4. These delays have the effect of making activities 1-7 and 4-7 continuous. Activity 7-8 is also made continuous by the necessary delay of event 7 to day 21. The resource requirement curve for this schedule and the resulting carpenter unit assignments is shown in Figure V-4.

Sometimes one assignment run may be sufficient and at times it may be desirable to repeat the process three or more times to determine the effect of certain changes. However, in most cases the necessary changes can be readily determined by inspection of the first run and only one more will be required to obtain the desired leveling. Some small changes in assignments may still be desirable after the second run but they can be made to the individual activities without necessitating an entire third run. It may

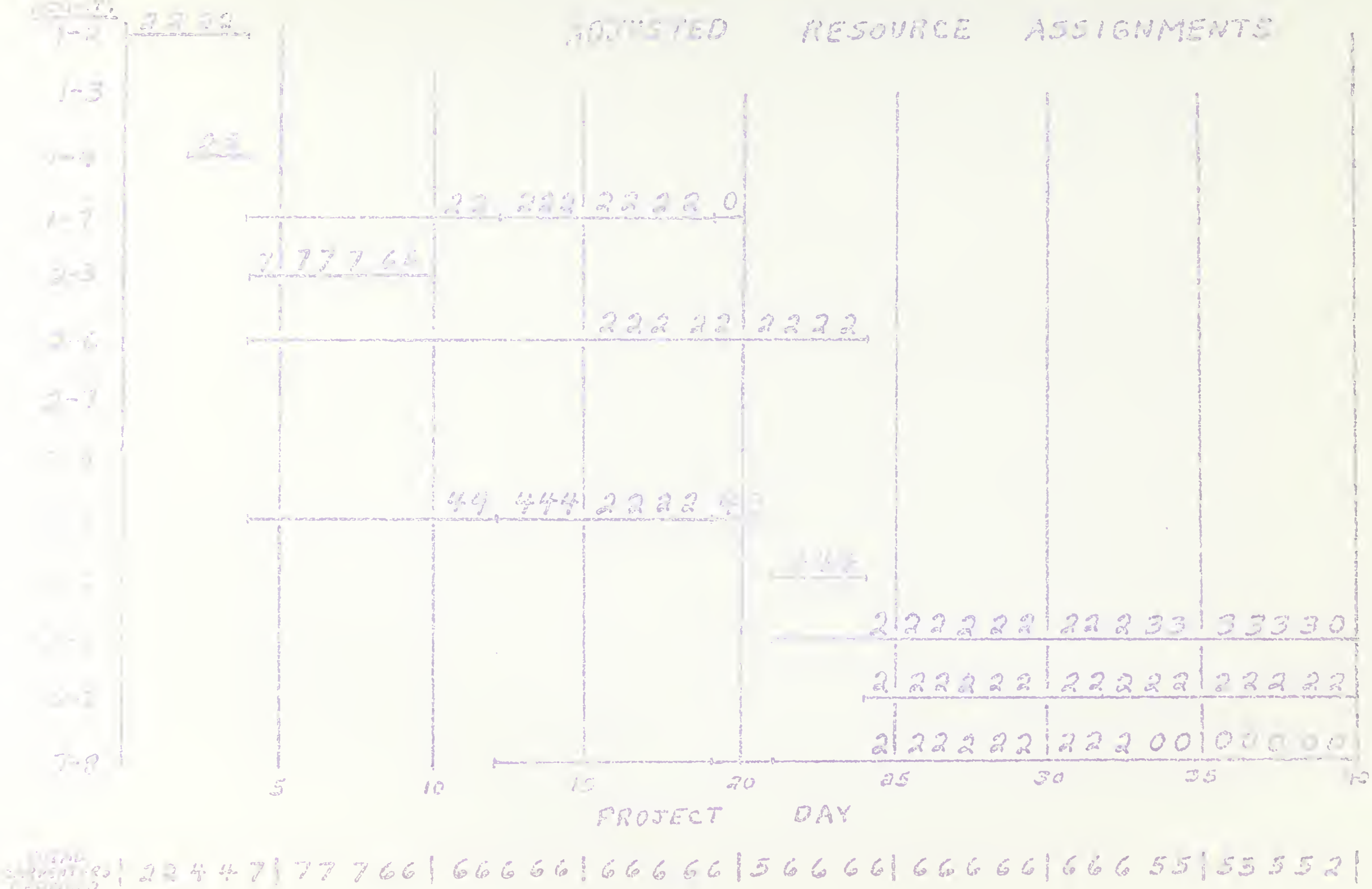
ADJUSTED RESOURCE ASSIGNMENTS
1-2
2 2 2 2
1-3
1-4
2 2
1-7
2 2 2 2 2 2 2 2 2 2 0
2-3
7 7 7 7 6 6
3-6
2 2 2 2 2 2 2 2 2
2-7
4 4 4 4 4 2 2 2 2 6
2 2 2 2 2 2 2 2 2 2 3 3 3 3 3 3 0
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 2 2 2 2 2 0 0 0 0 0 0 0
7-8
5
10
15
20
25
30
35
40
PROJECT DAY
2 2 4 4 7 | 7 7 7 6 6 | 6 6 6 6 6 | 6 6 6 6 6 | 5 6 6 6 6 | 6 6 6 6 6 | 6 6 6 5 5 | 5 5 5 5 2

FIGURE V-3

FINAL RESOURCE USAGE

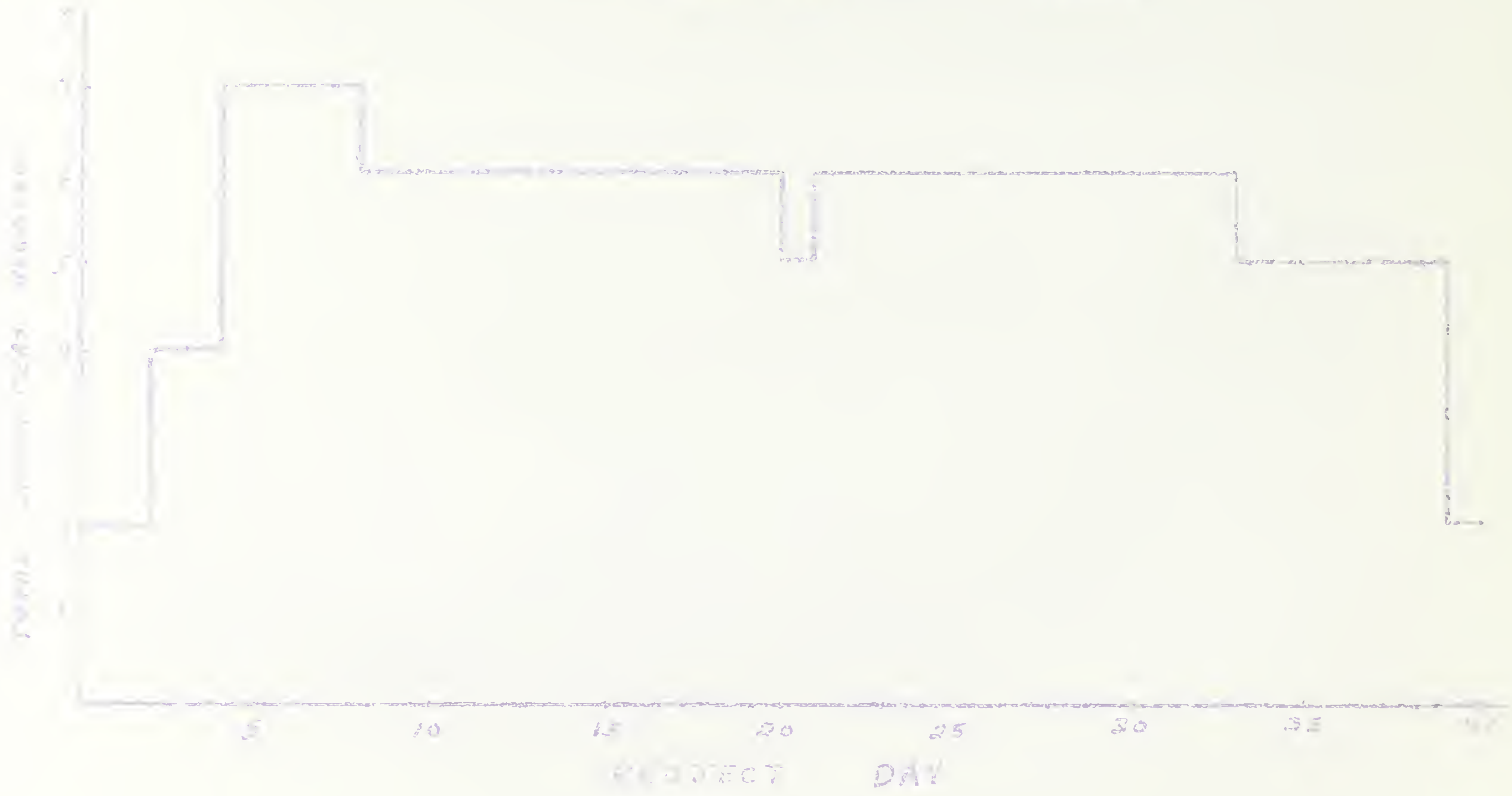

FIGURE V-4

GENERAL FLOW DIAGRAM

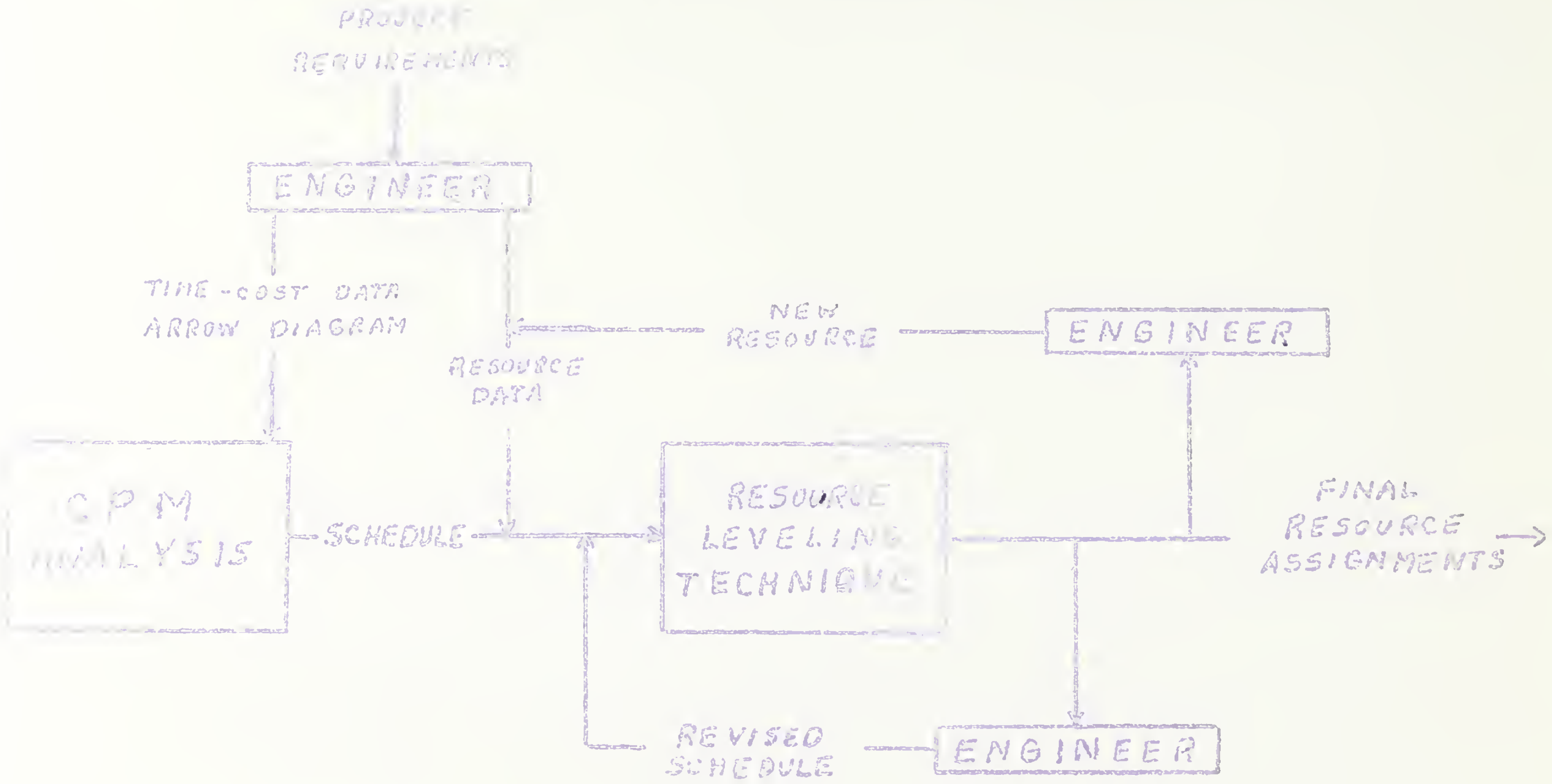

FIGURE V-5

be possible to level out some of the small fluctuations seen in Figure V-4 in this manner.

It is necessary to repeat this entire process for each critical resource. However, after the first resource has been assigned, the event times cannot be changed. They are fixed at the final value they were given in the assignment runs for the first resource considered. For this reason the first resource must be carefully chosen. Usually one resource is obviously most critical. Either the availability of this resource is sharply limited or the original requirements of the project fluctuate wildly. Possibly it is the resource with the largest total requirement for the project. If no single resource is obviously most critical then the first resource to be assigned can be chosen at random from those with the largest requirements in terms of total project man-days.

From inspection of the example problem it would not seem that this method is very effective. For a project as small as this is, there is still a relatively large amount of resource fluctuation. The fluctuation, though, would be of the same magnitude regardless of the project size. Therefore, on larger projects the method would appear much more effective because the fluctuations would not be as obvious. A general flow diagram of the entire technique is shown in Figure V-5.

VI

OTHER POSSIBLE TECHNIQUES

In the process of deriving the technique of resource leveling discussed in the previous section many possible schemes were tried. In this section some of the more promising of these will be discussed as well as some ideas to be kept in mind by anyone interested in the resource problem. It is hoped that perhaps some of these ideas could form a basis for other and possible better techniques of resource leveling.

One possible addition to the technique presented would be the computation of a daily project quota. That is, for each day, the number of resource units remaining to be assigned to the entire project would be divided by the remaining length of the project. The figure obtained would then be used as a revised desired resource level. Initially the project quota would be equal to the original desired resource level. However, if it is necessary to exceed the desired resource level as in days 4 to 8 of the example project, the project quota may decrease in the remaining days of the project. Using the daily project quota as the desired resource usage level would eliminate the sharp drop seen at the end of the project in Figure V-4.

The following revision could be made in the day-by-day assignment of resource units to activities. Instead of assigning each activity its quota and possibly reaching the desired resource level before all activities have been assigned units, the units available could be assigned to all activities in progress in a ratio proportional to the quota of each activity. In this manner all activities in progress would be assigned some resource units, even though it may not be as great a number as the quota. In this case some method would be necessary to eliminate the assignment of non-integral values.

Another possibility is to use a technique, such as Kidd's 333, to adjust event times before beginning to assign resource units to the activities. For the purpose of adjusting event times to make optimum use of floats, a constant crew size would have to be assumed for each activity. However, after the optimum event times are set, assignment of resource units could proceed as in the technique of Section V.

So far, these techniques all make use of a basic critical path schedule. Perhaps the Critical Path Method could be ignored and a technique devised which determines an optimum schedule on the basis of level resource usage. One could begin with an arrow diagram similar to that in

the Critical Path Method. Then instead of constructing a cost-time curve, a curve of resource usage versus time could be determined for each activity. This curve would be very similar to the time-cost curve in most instances, however, there would be some important differences. In the case of the time-cost curve a constant or average crew size must be assumed for each activity. It is the point where this average value becomes greater than the maximum efficient crew size that the cost of an activity begins to rise. However, as shown in Figure II-2, only a few finite points are actually computed and straight line segments are assumed between these points. In this manner the curve is continuous in straight line segments. This is, at best, an inaccurate assumption. Consider the flat portion of the curve where 48 man-days are required to complete this activity. This activity can be completed in 8 days with 6 men or 12 days with 4 men, but it cannot be completed at any time between these two durations using a constant sized crew. Therefore, it might be assumed in any cost-time curve or resource usage-time curve that these curves are not continuous but instead a series of isolated points. Clark (2) suggests that such a curve should be a continuous hyperbola. This indicates that an activity could be lengthened indefinately and that the cost or manpower required would decrease

continuously as the activity is lengthened. This is, of course, completely unrealistic since manpower can decrease only in finite integral steps. Also, there are definite maximum and minimum limits on the length of any activity. In addition, as has been previously stated, the cost of an activity will begin to increase at unreasonably long durations.

Using a plot of resource usage versus time for each activity, a process similar to the Critical Path Method could be followed to obtain a schedule which is optimum from the point of view of resource leveling. Least cost would be a secondary concern and would follow naturally from a least resource usage schedule because of the basic dependence of cost on resource usage. At one point durations longer than those obtainable with an efficiently sized crew were considered. It was felt that one might initially start at the longest possible duration for each activity. However, the long durations were later discarded because they would require greater manpower and therefore greater cost than some shorter durations for the same activity. For this reason they would almost never be included in any optimum schedule. Time and effort can therefore be saved in neglecting them.

The following method is therefore suggested as a possible solution to the resource leveling problem. First the arrow

diagram is drawn as in the Critical Path Method. Then a plot of resource usage versus duration is constructed for each activity, consisting of isolated points. The greatest duration on this plot is that one corresponding to the minimum efficiently sized crew. Then, using this greatest duration as the scheduled duration for each activity, a schedule is derived. This is the base schedule from which the process now proceeds. For this schedule, a resource usage curve is constructed for the most critical resource. In this method only one resource can be leveled and therefore it is best for projects with only one critical resource. All activities are now using the minimum efficiently sized crew throughout their duration and constant crew sizes will be used for all activity durations in this method. This is why only certain isolated durations may be used for each activity. When the resource usage curve is constructed it is enclosed in an envelope. The curve and its envelope might appear as shown in Figure VI -1. The envelope is shown as a dotted line. The area under the envelope indicates the resource requirement of the project if a constant level is to be maintained throughout. This first curve shows a great deal of unused resource if this level is maintained. However, now using a method similar to those used in the Critical Path Method, the project is shortened in steps

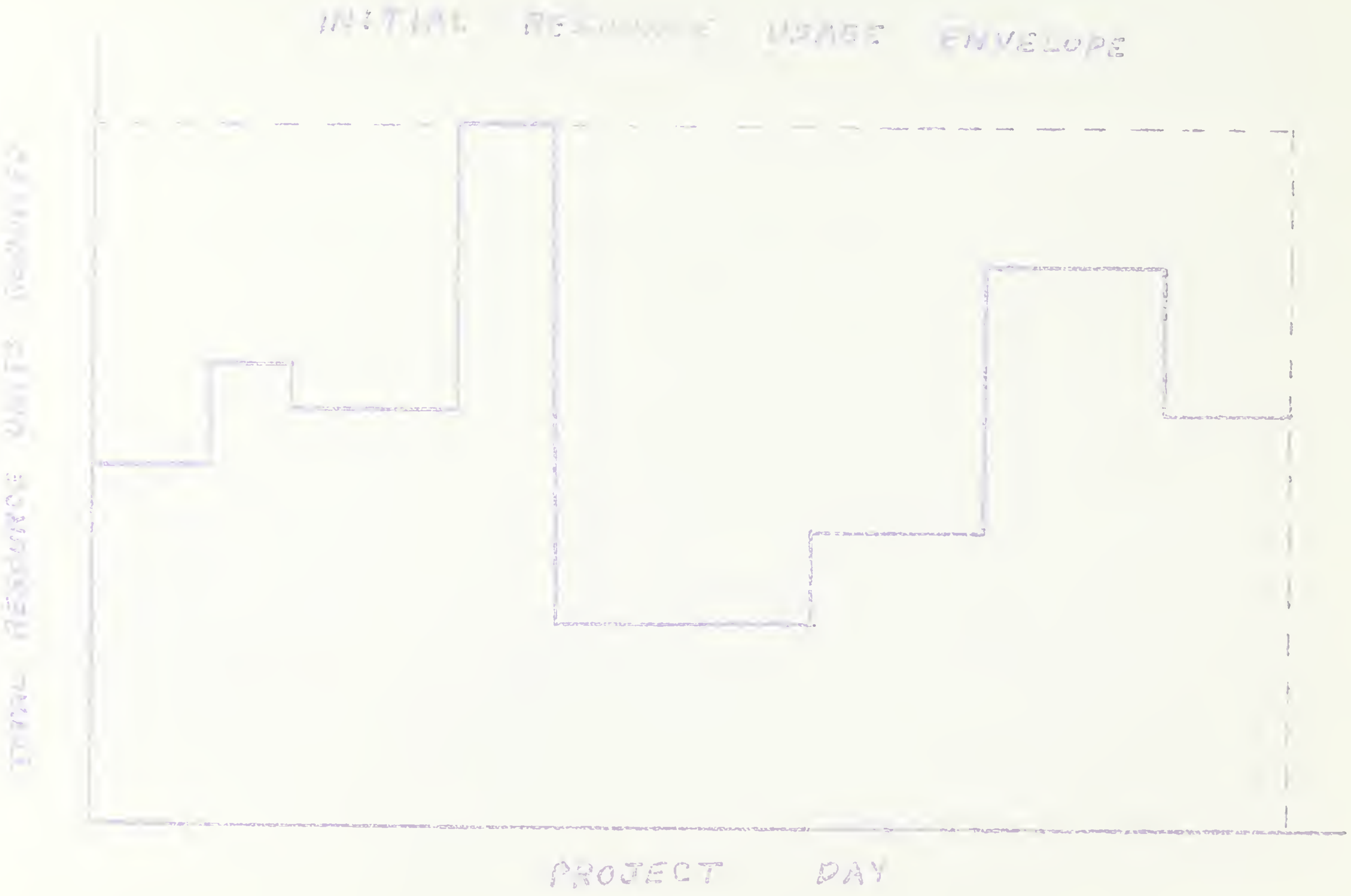
INITIAL RESOURCE USAGE ENVELOPE
TOTAL RESOURCE UNITS REQUIRED
PROJECT DAY

FIGURE XII-1

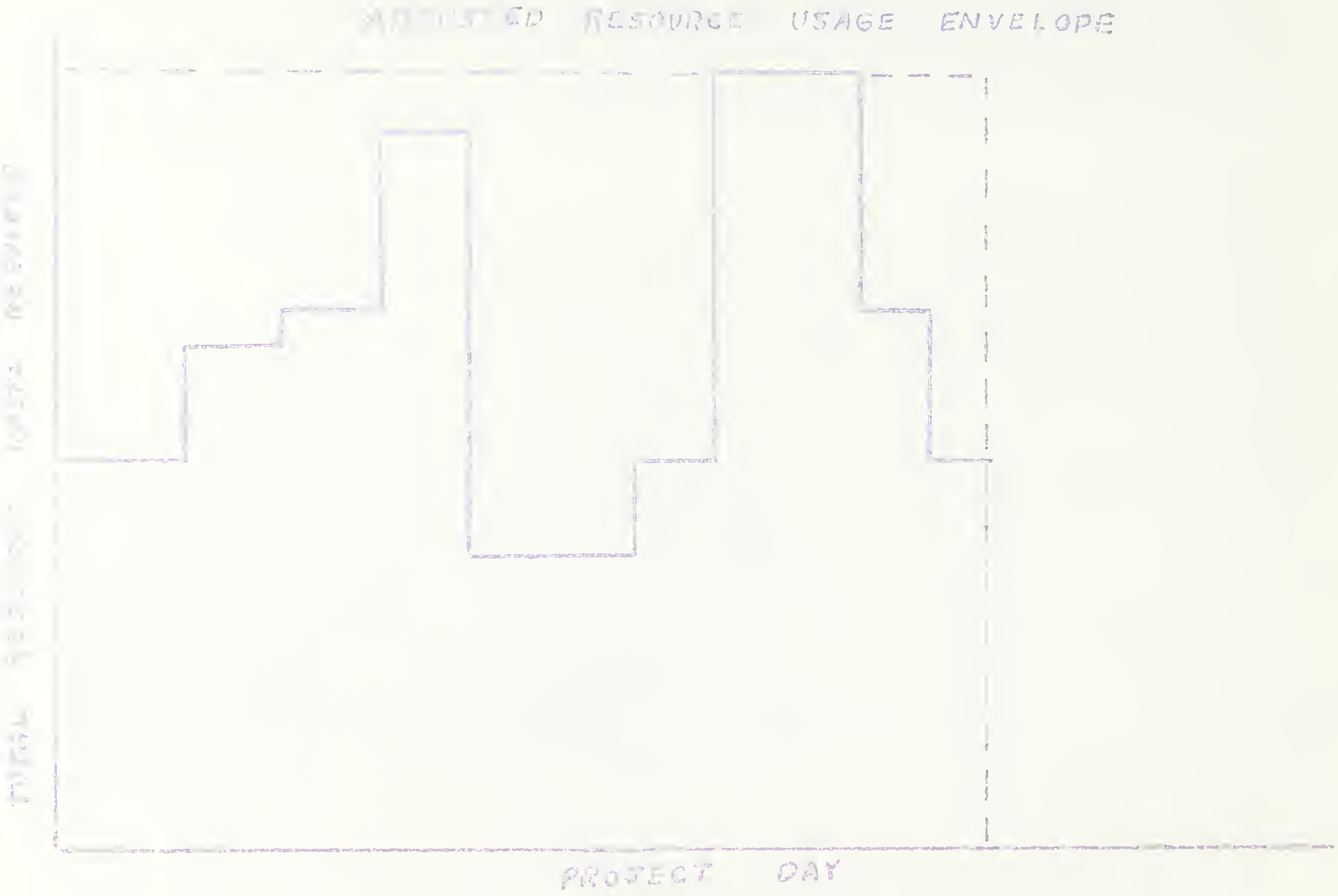
ALLOTTED RESOURCE USAGE ENVELOPE
TOTAL PROJECT DAILY RESOURCE
PROJECT DAY

FIGURE VI-2

by shortening activities on the critical path. The criteria for choosing which activity to shorten first will have to be established. Each time the project is shortened, another resource usage curve is drawn and enclosed with an envelope. This process is continued as long as the area under the envelope continues to decrease. The area under the resource usage curve should remain practically constant or begin to increase slightly, but the area under the envelope should decrease. The maximum resource level of the envelope may increase as the project duration decreases, however. Figure VI-2 shows a possible curve and envelope after shortening the project by a few steps. When the minimum area under the envelope is obtained, the process is complete and the schedule obtained at this point is considered optimum. This process could be refined more by adding a maximum limit on the resource level attained by the envelope or by the addition of a method to level small fluctuations in the resource usage curve.

VII

CONCLUSION

Methods of operational planning have advanced steadily for the last several decades. However, it is only recently that any serious work has been done in the problem area of resource or manpower scheduling. Even now, most methods of solving this problem have proven unsuccessful. It would appear, in retrospect, that the reason for this lack of success is due to just one factor - the assumption that activity crew sizes must remain constant. This assumption must be discarded in order to accomplish any reasonable amount of resource leveling. The actual technique presented in section V of this paper is fairly arbitrary. Once the assumption of variable crew sizes is allowed, a wide field of possibility opens up. Resources can now be allocated to activities when possible and necessary where previously only small adjustments in activity times were possible.

The technique presented in section V would appear to be fairly successful in leveling resources for the example project. Figure V-4 gives good indication of this. However, more information was obtained by testing this method on an actual project. The project used was the construction

of a small three floor apartment building. The project had 68 events and 104 activities. On a project such as this which is relatively small in comparison to most construction projects, the technique encountered one serious difficulty. It was found that a great number of the activities in this project were critical and that no resource was required continuously throughout the project. Therefore, few activities could be lengthened and great gaps existed in all the resource curves where none of this resource was required. On a project such as this, the technique has little value. In fact, any of the methods described in section IV would meet with approximately the same degree of success. Possibly a combination of a float adjustment method and the leveling technique would gain the best results.

In spite of a lack of success on this specific small project, it is still felt that the technique would be extremely effective on most projects, particularly those of larger size. In order to test the technique on larger projects, it must be converted into an operating computer program. The method was developed with this fact in mind. For this reason certain techniques were used to make it easily adaptable to computer logic. It is hoped that in the near future, the method will be programmed for computer solution,

thereby greatly increasing its value. In the process of preparing the computer program, certain refinements, including some suggested in section VI, could be included in the technique.

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